



Atomic Energy
Control Board

Commission de contrôle
de l'énergie atomique

P.O. Box 1046
Ottawa, Canada
K1P 5S9

C.P. 1046
Ottawa, Canada
K1P 5S9

INFO-0167-1

DETERMINATION OF THE CONTRIBUTION OF
LONG-LIVED DUST TO THE COMMITTED DOSE
EQUIVALENT RECEIVED BY URANIUM MINE
AND MILL WORKERS IN THE ELLIOT LAKE
AREA -- VOLUME 1 -- REPORT

by

Philippe J. Duport

and

Eric Edwardson

REPORT

November 26, 1985

DISCLAIMER

"The Atomic Energy Control Board is not responsible for the accuracy of the statements made or opinions expressed in this publication and neither the Board nor the authors assume liability with respect to any damage or loss incurred as a result of the use made of the information contained in this publication"

ABSTRACT

This study was aimed at determining the physical characteristics of airborne long lived dust and their dosimetric implications.

In the first part of this study, the physical characteristics of alpha-emitting long-lived dust present in uranium mine and mill atmospheres were investigated. In total, 91 air samples were taken on open face filters for the determination of gross alpha activity parameters (concentration and radionuclide make-up), and 43 air samples were taken using a Cascade Impactor for the determination of the aerosol size distribution and of the radionuclide make-up per class of particle dimension. It was found that airborne long-lived dust presents a wide range of Activity Median Aerodynamic Diameters (AMAD), usually with large dispersion parameters (Standard Geometric Deviation). In underground locations, AMADs range from 5 to 10 micrometers, whereas in mills AMADs are close to 7 micrometers.

From the radionuclide make-up of long-lived aerosols, their AMAD and the ICRP 30 lung dosimetry model, it was found that the DAC in underground locations ranges between 1290 mBq.m^{-3} and 1640 mBq.m^{-3} of alpha activity. In mill workplaces, the DAC is 2360 mBq.m^{-3} of alpha activity.

Due to the extreme variability of air concentration and dimension of alpha-emitting long-lived dust in uranium mines and mills, and should individual exposures need to be assessed, the use of a continuous personal monitor should be considered.

RÉSUMÉ

Le but de cette étude était de déterminer les caractéristiques physiques des poussières radioactives à vie longue et leurs implications concernant la dosimétrie.

La première partie de cette étude est consacrée à la détermination des paramètres physiques des poussières radioactives à vie longue présentes dans l'atmosphère des mines d'uranium et des usines (concentration dans l'air, proportion des différents radioéléments).

Durant la campagne de prélèvement, 91 échantillons de poussière ont été collectés directement sur filtre, pour la mesure de la concentration et la détermination de la composition des radioéléments, et 43 échantillons ont été collectés au moyen d'un impacteur en cascade, pour déterminer la distribution granulométrique des poussières en dimension et la répartition des radioéléments en fonction de la taille des particules. On a trouvé que l'AMAD (diamètre aérodynamique median en activité) était très variable (grande déviation standard géométrique). Dans les mines, l'AMAD varie de 5 à 10 micromètres, tandis que dans les usines de concentration, il est voisin de 7 micromètres.

Les dimensions de l'aérosol et la composition en radioéléments ont été utilisés pour calculer la Concentration Dérivée dans l'Air des poussières à vie longue en utilisant le modèle dosimétrique du poumon présenté par la publication CIPR 30. Dans les mines souterraines, la CDA pourrait varier de 1290 à 1640 mBq.m^{-3} d'activité alpha. Dans les usines, la CDA pourrait être 2360 mBq.m^{-3} d'activité alpha.

En raison de la grande variabilité de la concentration de poussières à vie longue dans l'air et de leurs dimensions, un appareil

de prélèvement individuel devrait être envisagé dans le cas où l'exposition individuelle aux poussières à vie longue doit être mesurée.

LIST OF CONTENTS

	<u>Page</u>
Abstract/Résumé	ii
List of contents	v
List of tables	x
List of figures	xii
Introduction	xiii
Glossary of terms	xv
A. CHARACTERIZATION OF LONG LIVED DUST	1
1 Dust Sampling	1
1.1 Pilot Sampling	1
1.2 Size distribution of Long Lived Dust	2
1.3 Abnormalities in size distribution measurement	5
2. Sample analysis - Procedure and equipment	6
2.1 Dust mass determination	6
2.2 Gross alpha counting	6
2.3 Activity distribution	7
2.4 Alpha spectrometry	7

		<u>Page</u>
2.5	Neutron activation analysis	10
3.	Sampling Environment - Mining and milling methods...	10
3.1	Mining Methods and Ventilation Systems.....	10
3.2	Milling Method	10
3.3	Air Sampling.....	11
3.3.1	Sampling locations	11
3.3.2	Sampling difficulties	13
3.3.2 a)	Underground Locations	13
3.3.2 b)	Mills	14
4.	Results	14
4.1	Total airborne dust and alpha activity concentrations	14
4.2	Dust mass distribution	16
4.3	Gross alpha activity distribution	17
4.4	Alpha spectra analysis	19
4.4.1	Estimation of Radon and Thoron gas emanation from ore dust	19
4.5	Neutron activation analysis.....	20

B	DETERMINATION OF THE COMMITTED EFFECTIVE DOSE EQUIVALENT INCURRED FROM EXPOSURE TO AIRBORNE LONG-LIVED DUST	22
1.	Basis for limiting occupational exposure to ionizing radiation.....	22
2.	Secondary and derived limits for the control of internal dose	24
2.1	Annual Limit on Intake (ALI)	24
2.2	Derived Air Concentration (DAC)	25
3.	Methodology for determining the Committed Effective Dose Equivalent	26
3.1	Radiological characteristics of the Elliot Lake ore	28
3.2	Determination of the ALI for a mixture of radionuclides..	35
3.3	Errors introduced in neglecting radionuclides with high ALI	39
4.	Derived Air Concentration of Uranium ore dust in air..	41
5.	DAC & practical aspects of monitoring long-lived uranium dust concentration in air	43
5.1	Measurement Techniques	43

5.2	DAC for global radioactivity and DAC "Alpha".....	44
5.3	Other approaches for determining ALI values.....	47
5.3.1	NRPB approach.....	47
5.3.2	Hannibal's approach	48
5.3.3	Johnson's approach	48
5.3.4	Jammet's interpretation of ICRP 30 Publication.....	51
5.3.5	Comparison of ALI values from the different authors..	51
6.	ALI and DAC for Long Lived Dust in uranium concentrate areas of uranium mills	53
C	CONCLUSIONS.....	55
1.	Underground locations.....	55
2.	Surface locations	56
2.1	Ore preparation areas in the mill.....	56
2.2	Uranium concentration areas	57
3.	General Considerations.....	57
D.	REFERENCES.....	58

VOLUME II - APPENDICES

Appendix A	Cascade Impactors
Appendix B	Abnormalities in impactor size distribution analysis using glass fibre collecting media
Appendix C	Experimental results
Appendix D	Neutron Activation Analysis
Appendix E	Calculation of the ALI for a mixture of radionuclides
Appendix F	Dosimetric model for the respiratory system
Appendix G	ALI detailed tables

LIST OF TABLES

Table #	Title	Page
1	Aerodynamic Equivalent Particle Diameters with Glass Fibre Collection Substrates	3
2	Sampling Locations in Underground Uranium Mines	12
3	Sampling Locations in Uranium Mills	13
4	Radon and Thoron Emanation Rates from Ore Dust	20
5	Weighting Factors Recommended by the Commission for Stochastic Risks	24
6	Deposition Fractions of Aerosols in the Naso-Pharynx (Dn-p), Tracheo-Bronchial (Dt-b), and Pulmonary (Dp) Regions of the Respiratory Tract	27
7	Characteristics of the Elliot Lake Uranium Ore	28
8	U ²³⁸ Decay Series	30
9	U ²³⁵ Decay Series	31
10	Th ²³² Decay Series	32
11A	Summary of Tables 8,9,10 for Radionuclides with an ALI. Specific Mass Activities in Bq per gram of ore for each Decay Series.	33

118	Summary of Tables 8,9,10 for Alpha Activity Only.	34
12	ALI values for whole body dose for radionuclides of U^{238} , U^{235} and Th^{232} series with AMAD's of 1, 2, 5 and 10 microns, and their relative contribution to total activity.	37
13	Radionuclides with an ALI greater than 10^4 Bq and 10^5 Bq (AMAD of 1 micron)	40
14	Overestimation of ALI introduced by neglecting radionuclides with an ALI value greater than 10^4 Bq.	41
15	ALI values for Elliot Lake ore in Bq (Alpha + Beta)	42
16	DAC values for Elliot Lake ore in $mBq.m^{-3}$ (Alpha + Beta)	42
17	Total activity, "ALI" activity, and "Non-ALI" activity in uranium ore dust	46
18	ALI and DAC values determined by other authors	47
19	ALI values calculated by Johnson, according to the assumption indicated in section 5.3.3	50
20	Comparison of ALI values for the preponderating of the Elliot Lake ore and for the Elliot Lake ore dust.	52

LIST OF FIGURES

Fig No.	Title	Page
1	Mass and activity distributions	4
2	Alpha spectrum of calibration sources Th^{230} and Am^{241}	8
3	Alpha energy spectrum of a LLD sample collected underground	9
4	Alpha energy spectrum from a mill uranium concentrate packing area	9
5	Dust mass and alpha activity concentration at underground locations	15
6	Dust mass and alpha activity concentration in mill locations	16
7	Range of measured AMAD's for underground locations at Mine A	17
8	AMAD's for underground locations at Mines A and B.	18
9	AMAD's and σ_g for Mill A and B combined	18
10	Ratio of measured alpha activity to theoretical alpha activity.	21

1. Introduction

The mining and milling of uranium-bearing ores generates a number of radiation hazards. These hazards are classified into two groups: external radiation exposure from beta and gamma emissions affecting the whole body, and internal irradiation from inhaled short lived and long lived radionuclides that affect the respiratory tract. Alpha particles are of particular concern because they transfer their energy over a very short path, about 100 microns, thereby causing more damage to living tissues than penetrating radiation. The alpha emitters of the uranium and thorium decay series are divided into two groups: the short-lived alpha emitters with physical half-lives that are short compared with the self-clearance rate of the respiratory tract, and the long lived emitters with half-lives much longer than the self clearance rate of the respiratory tract.

In the North-American uranium industry the main consideration has been given to exposure to short lived radionuclides of uranium and thorium decay chains (radon and thoron daughters). Ongoing research has shown that exposure to radioactive long lived dust can also be significant. In the present work the term "exposure" has been used instead of "dose" because the dose effectively delivered to the lung during and after inhalation of airborne alpha emitters depends on many physical parameters, exposure being one of them. The application of radiation protection regulations (or recommendations) gives rise to the issue of how the exposure to ore dust in underground uranium mines and mills should be taken into account. This study deals with the quantification of some of the physical characteristics of long lived radioactive dust at two uranium mines and two mills. By measuring the dust concentration in the air, its size distribution and its radionuclide make up, it was possible to calculate the corresponding Committed Effective Dose Equivalent

(H50). From this, the Annual Limit on Intake (ALI) and the Derived Air Concentration (DAC) were determined for various mine and mill conditions.

The aim of this project as stated in the title was to determine the contribution of long lived radioactive dust to lung exposure in the mining and milling of uranium-bearing ores. A two step procedure was set up. The first step was to quantify the physical characteristics of long lived radioactive dust (LLD) present in the working environment. The second was to derive the Annual Limit on Intake and the Derived Air Concentration from the physical parameters of the dust and the use of the ICRP 30 dosimetric lung model.

Glossary of terms and symbols for internal dosimetry

Activity Median Aerodynamic Diameter (AMAD)

the diameter of a unit density sphere with the same terminal settling velocity in air as that of the aerosol particle whose activity is the median for the entire aerosol.

Annual Limit on Intake (ALI)

The activity of a radionuclide which taken alone would irradiate a person, represented by Reference Man, to the limit set by the ICRP for each year of occupational exposure.

Becquerel (Bq)

the special name for the SI unit of activity,
 $1 \text{ Bq} = \text{s}^{-1} \text{ (} 2.7 \times 10^{-11} \text{ Ci)}$.

Cells near bone surfaces (BS)

those tissues which lie within 10 microns of endosteal surfaces and bone surfaces lined with epithelium.

Committed Dose Equivalent (H_{50})

the total dose equivalent averaged throughout a tissue in the 50 years after intake of a radionuclide into the body.

Deposition probability (in lung region)

the fraction of the activity or mass of an inhaled aerosol which is deposited in a particular region of the lung.

Derived Air Concentration (DAC)

equals the ALI (of a radionuclide) divided by the volume of air inhaled by Reference Man in a working year (i.e. $2.4 \times 10^3 \text{ m}^3$). The unit of DAC is $\text{Bq}\cdot\text{m}^{-3}$.

Dose Equivalent (H)

the product of the absorbed dose, the quality factor (Q) and the product of any other modifying factors (N).
(currently $N = 1$.)

Dose Equivalent Limits

the maximum values of committed dose equivalent incurred in 1 year by individual organs (non-stochastic limits), and by the uniformly irradiated whole body (stochastic limit) of an occupationally exposed person, which are recommended in ICRP Publication 26 (1977).

gray (Gy)

the special name for the SI unit of absorbed dose.
 $1 \text{ Gy} = 1 \text{ J kg}^{-1} = 100 \text{ rad}$.

Lung Class (D, W or Y)

a classification scheme for inhaled material according to its rate of clearance from the pulmonary region of the lung.

Non-Stochastic effects

effects such as opacity of the lens of the eye for which the severity of the effect varies with the dose, and for which a threshold may therefore occur.

Quality Factor (Q)

the principal modifying factor (which depends on the collision stopping power for charged particles) that is employed to derive dose equivalent from absorbed dose.

Red Bone Marrow (active)

the component of marrow (assumed in this report to have a mass of 1500 g) which contains the bulk of the haematopoietic stem cells.

Reference Man

a person with the anatomical and physiological characteristics defined in the report of the ICRP Task Group on Reference Man (ICRP Publication 23).

sievert (Sv)

the special name for the SI unit of dose equivalent.

$1 \text{ Sv} = 1 \text{ J kg}^{-1} = 100 \text{ rem.}$

Source Tissue (S)

tissue (which may be a body organ) which contains a significant amount of a radionuclide following intake of that radionuclide into the body.

Specific Absorbed Fraction

the fraction of energy emitted as a specified radiation type in a source tissue which is absorbed in 1 g of a target tissue.

Specific Effective Energy (SEE (T, S))

the energy (MeV), suitably modified for quality factor, imparted per gram of a target tissue (T) as a consequence of the emission of a specified radiation (i) from a transformation occurring in source tissue (S).

Stochastic Effects

malignant and hereditary disease for which the probability of an effect occurring, rather than its severity, is regarded as a function of dose without threshold.

Target Tissue (T)

tissue (which may be a body organ) in which radiation is absorbed.

Transfer Compartment

the compartment introduced (for mathematical convenience) into most of the metabolic models used in this report to account for the delay between radioactive material entering body fluids and its deposition in particular tissues.

Weighted Committed Dose Equivalent ($w_{TH50,T}$)

the product of the weighting factor and the committed dose equivalent for a specified tissue.

Weighting Factor (w_T)

the ratio of the stochastic risk arising from irradiating tissue T to the total risk when the whole body is irradiated uniformly.



A. CHARACTERIZATION OF LONG LIVED DUST

To estimate the dose to the lung, a number of parameters must be quantified. These include the dust concentration in the air, the size distribution and the radionuclide make up of the dust. Total dust concentrations were measured on open-face filter samples. Particle size distributions were measured using a cascade impactor, and the radionuclide make up was determined by alpha spectrometry and neutron activation analysis.

1. Dust sampling

1.1 Pilot Sampling

An initial set of aerosol samples were collected on open face filters at several work locations in two uranium mines and two mills. The dust was collected on preweighed 1.2 micron pore-size, cellulose nitrate filters. The filters were held in 47 millimeter diameter stainless steel filter holders. Sample volumes ranged from one to two cubic meters of air with sample duration ranging from 30 to 200 minutes. Flow rates used were from 5 to 30 liters per minute. Two types of sample pumps were used, the H & H battery operated or a Gast rotary vane vacuum pump, operating under 110 volts A.C.

Analysis of these initial samples gave information on the total dust concentration and the long lived alpha activity concentrations. This information was used to understand sampling conditions and set up sample duration and flow rates for further sampling.

1.2 Size distribution measurement of Long Lived Dust

Particle size distribution measurements were carried out using a Sierra Model 210 Cascade Impactor. The aerosols were drawn into the impactor using a 110 volt A.C. powered vacuum pump with a maximum flowrate of 30 LPM and a vacuum of 635 mm of Hg. On each stage the fine particles were collected on preweighed glass-fibre substrates. Type A glass-fibre collection substrates were used exclusively for impactor sampling for practical reasons i.e., ease of handling, reduction of particle bounce, and relatively low mass. An outline of the theory governing the functioning of Cascade Impactors is given in Appendix A. The impactor was operated in either the 7 or 8 stage configuration without the preseparation cyclone stage. The maximum flowrates for various stage configurations are given in Table 1. The cut-off diameters for each stage are given as aerodynamic equivalent particle diameters at 50 percent collection efficiency, assuming a particle density of 1.

Table 1: Aerodynamic Equivalent Particle Diameters in Microns at 760 millimeters of mercury and 25°C with Type A Glass Fibre Collection Substrates.

Impactor Stage	Flow Rate (l/min)			
	7	10	14	21
1	18	15	13	10
2	11	9.2	7.8	6.3
3	4.4	3.7	3.1	2.5
4	2.65	2.2	1.8	1.4
5	1.7	1.4	1.2	0.96
6	0.95	0.76	0.63	0.50
7	0.53	0.42	0.34	0.25
8	0.32	0.25	0.15	---

The mass increase of each collection substrate was taken as the mass of fine particles collected. The mass on all stages was then totalled and the percent collected on each stage was calculated. The size distribution was determined by plotting the cumulative percent less than the cut off diameter, against the cut off diameter for each stage on log-probability graph paper. The Mass Median Aerodynamic Diameter (MMAD) and the Geometric Standard Deviation (σ_g) were determined from the size distribution plots.

The MMAD is an overall measure of the size of fine particles (whether large or small) and is defined as the particle diameter corresponding to the 50th percentile on the size distribution plot. σ_g is the ratio of the particle diameters (D_p) corresponding to the 50th and 16th percentiles on the plot.

$$\sigma_g = \frac{D_p(50\%)}{D_p(16\%)}$$

This is a measure of the spread of the particle size distribution. If σ_g is equal to 1 the aerosol is monodispersed, in general σ_g is greater than 1. An example of a log-normal distribution is given on Fig. 1. The complete set of experimental results regarding the physical characterization of Long Lived Dust is given in Appendix C.

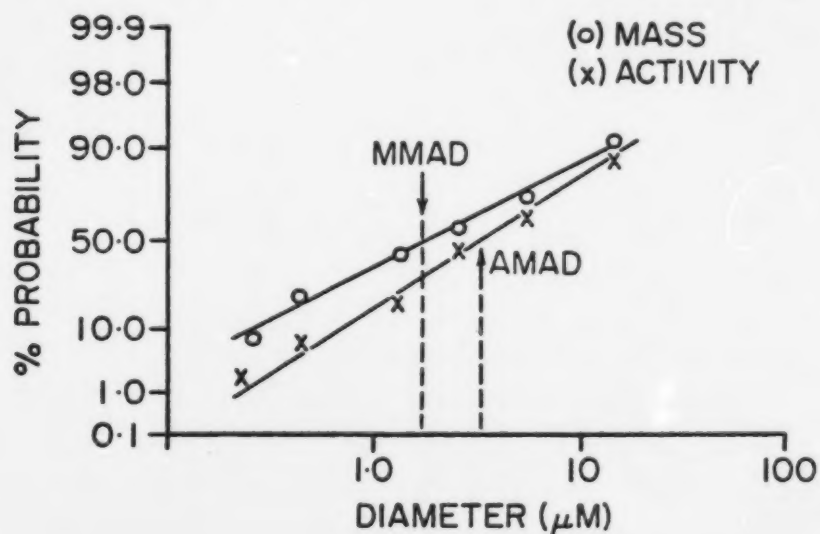


Fig. 1 Mass and activity distribution

1.3 Abnormalities in size distribution measurement

While using the cascade impactor for dust sampling it was expected that the net mass collected on the lower stages of some samples would be in the range of sensitivity of the microbalance. On a number of samples a negative mass was observed on the substrates of lower stages. A set of tests were set up to determine the cause of the negative mass measurements. Appendix B gives details of the tests and results. The observations were:

- the mass loss was fairly consistent on all stages, but showed up on the lower stages where generally less dust mass was collected.
- the mass loss was in the order of 50 micrograms per substrate.

It is thought that the mass loss is due to the loss of substrate material, through two different mechanisms:

1. loose glass fibres were blown off, in the first 10 to 20 minutes of impactor operation.
2. fibres adhered to the rubber "O" rings on the impactor stages during disassembly of the cascade impactor.

The loss of substrate material led to an overestimation of the MMAD. This error was less than 10% providing 500 micrograms of dust or more was collected by each impactor stage. MMAD's were not determined for samples with negative masses.

It must be pointed out that the errors associated with the MMAD determination do not affect the Activity Median Aerodynamic

Diameter (AMAD). The AMAD's were determined from the gross alpha count per stage, not from the mass that was measured.

2. Sample analysis - Procedure and equipment

2.1 Dust mass determination

Dust samples were collected in the mine with the collecting surface or inlet held parallel to the direction of airflow. Blank and dust loaded open face filters and impactor substrates were weighed on a Cahn 26 microbalance. Samples were stored in the controlled lab environment for a minimum of 24 hours before being weighed. The lab was maintained between 21° and 24°C with the relative humidity ranging between 45 and 50 percent. The mass of dust collected was determined by the difference in the mass of the blank and dust loaded filters and substrates. Relative errors in dust mass determination ranged from 1 to 100 percent of the collected mass depending on the total mass collected. An example of dust mass distribution is given on Fig. 1.

2.2 Gross alpha counting

The gross alpha activity was determined using a Ludlum Model 2200 Scaler and a Model 43-10 Alpha Sample Counter. A Hewlett-Packard HP-41 calculator and printer were added to the system using a Ludlum Model 322 interface. The counting efficiency of the system was determined using Americium²⁴¹ and Thorium²³⁰ calibration sources. Detector to source and detector to sample geometries were also taken into account. The overall efficiency ranged from 0.38 to 0.40 for open face filter and cascade impactor samples. The efficiency was checked daily and the background ranged between 3 and 6 mBq. The alpha activity concentration was determined by relating the sample activity in Becquerels to the sample volume in cubic meters of air sampled.

Samples were held for a minimum of four days before being counted for gross alpha activity. This allowed radon and thoron daughters collected during sampling to decay away.

2.3 Activity distribution

The gross alpha activity measured on the collection substrates of cascade impactor samples enabled the determination of the activity distribution. The percentage activity for each impactor stage was determined. The cumulative percent less than the cut off diameter was plotted against the stage cut off diameter on log-probability paper. The Activity Median Aerodynamic Diameter (AMAD) and the corresponding σ_g were determined for all impactor samples. An example of Activity Diameter distribution is given on Fig. 1.

2.4 Alpha spectrometry

The alpha emitting radionuclides of the uranium and thorium decay chains each emit an alpha particle of specific energy. Alpha emitting radionuclides can be identified by analyzing the spectrum of alpha energies. The alpha spectrometry was carried out using a ruggedized surface barrier detector from EG&G Ortec. The detector was housed in a vacuum chamber and coupled with a Multichannel Analyser Model 1056 C from D.S. Davidson Ltd. Spectra have been recorded on tape and printed on hard copy using a X-Y recorder. The instrument was calibrated for geometric counting efficiency and peak resolution with alpha sources of known activity and energy (Am^{241} , Th^{230}). Figure 2 shows the spectra of the two calibration sources. Calibration was checked before and after each sample was analysed.

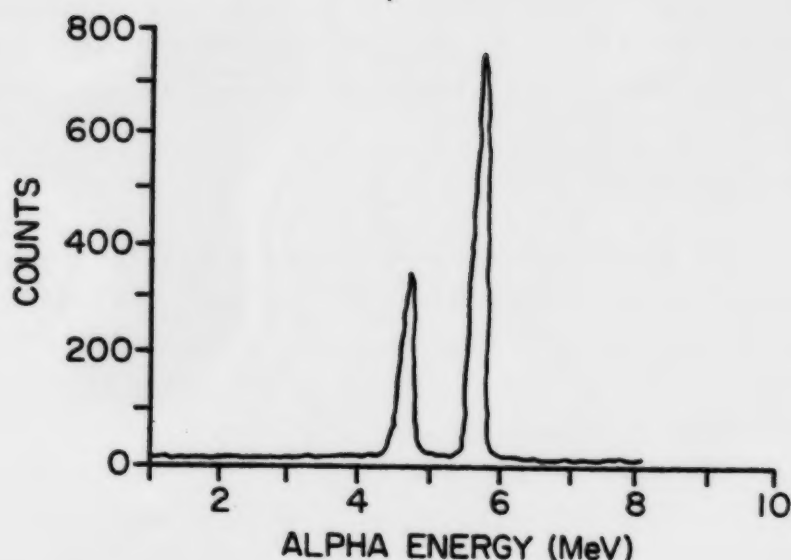


Fig. 2 Alpha spectrum of calibration sources Th^{230} and Am^{241}

The sharpness of spectra varied greatly from sample to sample. Analysis of the more distinct spectra included:

- (1) Identification of some radionuclides.
- (2) Estimation of radon and thoron gas emanation from dust samples by comparing Po^{214} and Po^{216} alpha counts to the total alpha count.

Samples from all underground areas and surface crushing and grinding locations have similar alpha spectra. (See Figure 3). For samples from areas in the mills where uranium was already separated from all the other materials, the two main peaks on the alpha spectra were those of Uranium²³⁸ and Thorium²³². (See Figure 4).

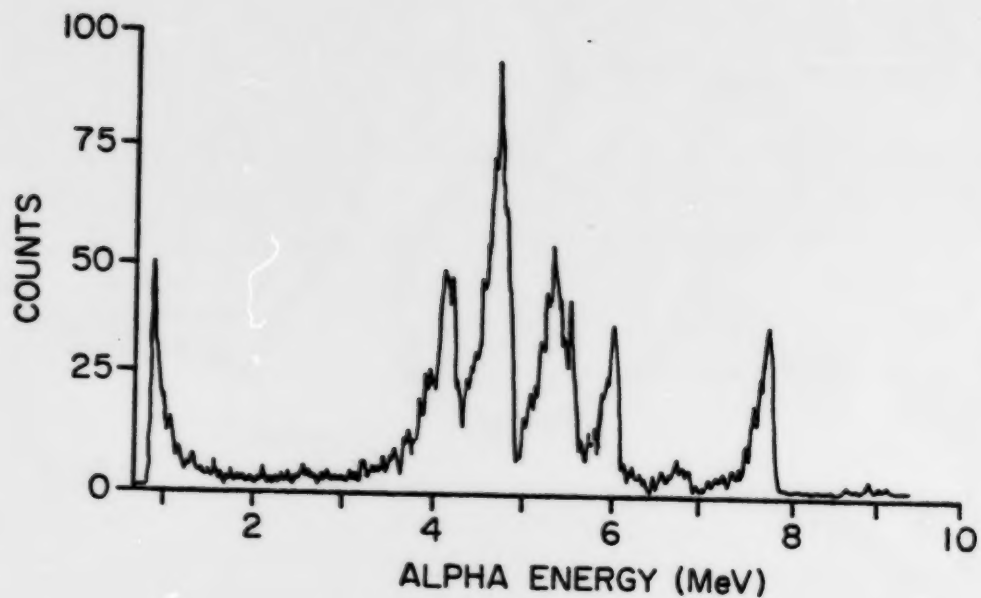


Fig. 3 Alpha energy spectrum of LLD sample from a uranium mine

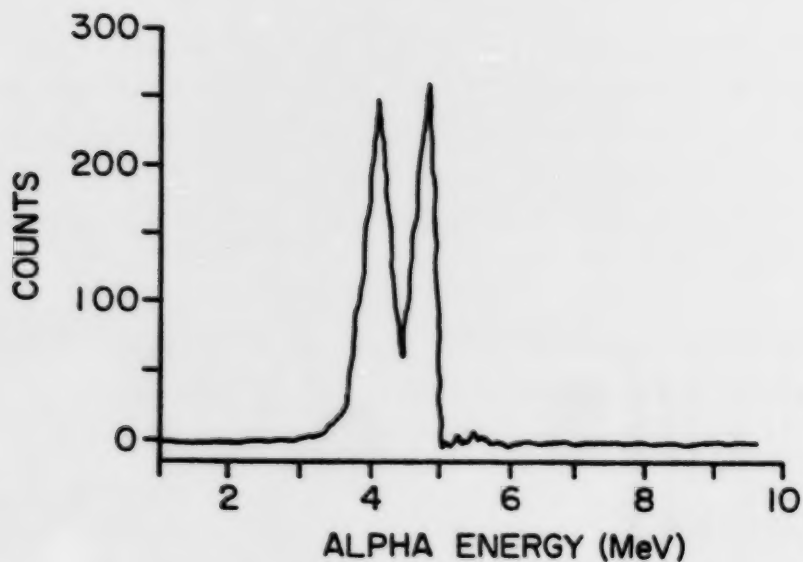


Fig. 4 Alpha energy spectrum from a uranium mill concentrate packing area

2.5 Neutron activation analysis

A subset of open face filter and cascade impactor samples was sent to Becquerel Laboratories Inc., Mississauga, Ontario. For U^{238} and Th^{232} mass determination using Neutron Activation Analysis.

From the mass of U^{238} and Th^{232} measured the total alpha activity for each sample was estimated. These results were compared to the gross alpha activity measured by scintillation counting. On the average there was good agreement between the two methods, although wide discrepancies were observed on individual samples. (Appendix D)

3. Sampling Environment - Mining and Milling Methods

3.1 Mining methods and ventilation systems

The mining methods were similar at both mines where sampling took place. Both mines operate using mechanised room and pillar mining. Mine B was returning to conventional mining methods where the ore vein was tapering out. Mine A hauled muck via trackless vehicles and/or beltways. Mine B utilized trackless vehicles or ore trains to move the muck.

The ventilation systems were push-pull systems with the mines being kept at a positive pressure. The ore was crushed at jaw crushers at both mines before being sent to surface.

3.2 Milling method

Both mills extract the uranium from the ore using an acid leach process. In general the ore goes from jaw crushing to cone crushers. The next step is grinding, usually rod and pebble

mills or autogenous grinding. At this point the ore is in slurry form. The slurry is dewatered to a defined water concentration and sent to the acid leaching tanks. The mill pulp then goes through ion exchange areas and the uranium is collected. The uranium concentrate is collected on drum filters, then dried and packed.

3.3 Air sampling

3.3.1 Sampling locations

Most of the sample locations were chosen jointly by CAIRS and the Mining Companies involved. The Mining Companies were extremely cooperative in allowing and assisting in the access to underground and mill locations. Sample locations covered a number of work areas. The sample locations for the 91 open face filter samples and 43 cascade impactor samples are given on tables 2 and 3.

Table 2: Sampling locations in underground uranium mines

	Mine A		Mine B		TOTAL
	O.F.	C.I.	O.F.	C.I.	
Active Stope *	6	3	3	3	15
Rock Breaker	9	4	-	-	13
Jaw Crusher	13	4	2	2	21
Beltway	13	4	-	-	17
Haulage Drift	7	2	-	-	9
Main Air Intake	-	-	2	2	4
Main Air Exhaust	-	-	3	2	5
Refuge Station	4	-	-	-	4
Total	52	17	10	9	88

* Air sampling in active stopes covers several mining operations, such as drilling, mucking, scaling and roof bolting.

Table 3: Sampling locations in uranium mills

	Mine A		Mine B		
	O.F.	C.I.	O.F.	C.I.	TOTAL
Jaw Crusher	1	1	-	-	2
Cone Crusher	2	1	3	2	8
Screens	2	1	3	2	8
Grinding	1	-	2	2	5
Disk Filter	-	-	3	2	5
Drum Filter	2	1	2	-	5
Acid Precip.	1	1	4	2	8
Uran. Conc. Dry	1	1	-	-	2
Uran. Conc. Pack	2	1	-	-	3
Total	12	7	17	10	46

3.3.2 Sampling difficulties

Air Sampling in the underground and mill work environments involved overcoming a number of obstacles.

3.3.2 (a) Underground locations

The sampling pumps used in the study required 110 volt A.C. power, therefore sampling locations were chosen with power accessibility in mind. The mining companies generally use 550 volt power underground. At several sampling locations the companies supplied step- down transformers to supply the required voltage.

Ventilation methods used underground tend to carry dust fine particles through the mine. This adds a degree of uncertainty when analysing the dust from a single mining operation. Sample locations were chosen accordingly in an attempt to minimize the effects of cross contamination.

To collect a measureable quantity of dust on a cascade impactor sample, sampling duration ranged from 8 to 12 hours. This posed a problem where the underground workers were generally not in any location for more than 3 to 4 hours. In stopes, impactor samples consist of a number of work types including drilling, scaling, mucking and bolting.

3.3.2 (b) Mills

Power accessibility was not a problem in the mills, but many potential dust sources were generally quite close and usually within the same building.

4. Results

4.1 Total airborne dust and alpha activity concentrations

Total dust mass concentrations measured at underground sample locations were generally in the vicinity of $1000 \mu\text{g}/\text{m}^3$. Alpha activity concentration ranged between 10 and $800 \text{ mBq}/\text{m}^3$, with the average activity concentration at all locations being close to $100 \text{ mBq}/\text{m}^3$. Intake airways and some jaw crushing locations were fed with relatively fresh air and showed lower dust and activity concentrations. Fig. 5 displays the range of measured values for total dust and alpha activity concentrations at underground sampling locations. The symbols "O" and "Δ" indicate the arithmetic average of the observed values. The bars indicate the range of measured values. They are not error bars. The dust

and activity concentrations at jaw crushing, active stopes and rock breaker locations was generally proportional to the physical activity in these areas.

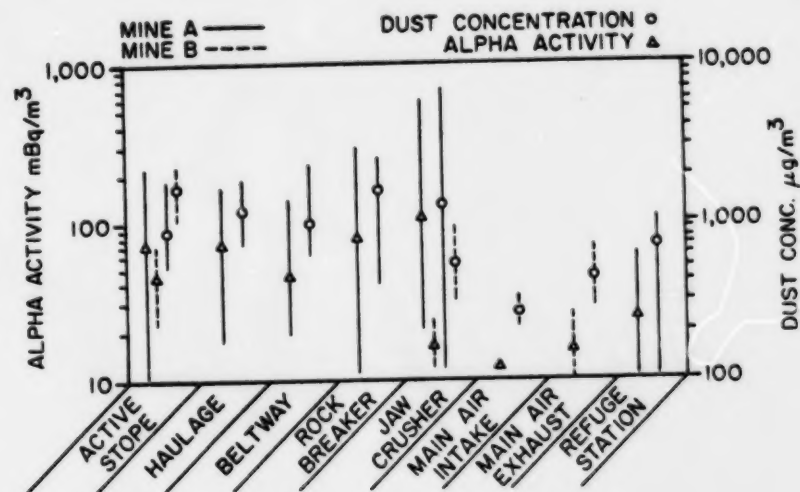


Fig. 5 Dust mass concentration and alpha activity concentration at underground locations. Note: Solid and dotted lines indicate the range of observed values.

It must be pointed out that total dust concentration includes all types of dust present in the mine atmosphere, including mineral dust, diesel smoke fine particles and any particles driven into the mine by the ventilation system.

Dust and alpha activity concentrations measured in the mill sampling locations are shown in Fig. 6. The dust concentrations ranged from 400 to 1000 $\mu\text{g}/\text{m}^3$. Alpha activity concentrations measured in the crushing and grinding areas ranged from 20 to 150 mBq/m^3 . In the mill circuit from leaching to concentrate packing areas the activity concentrations ranged between 100 and 800 mBq/m^3 . This higher activity concentration was expected as the mill pulp becomes more concentrated in uranium content.

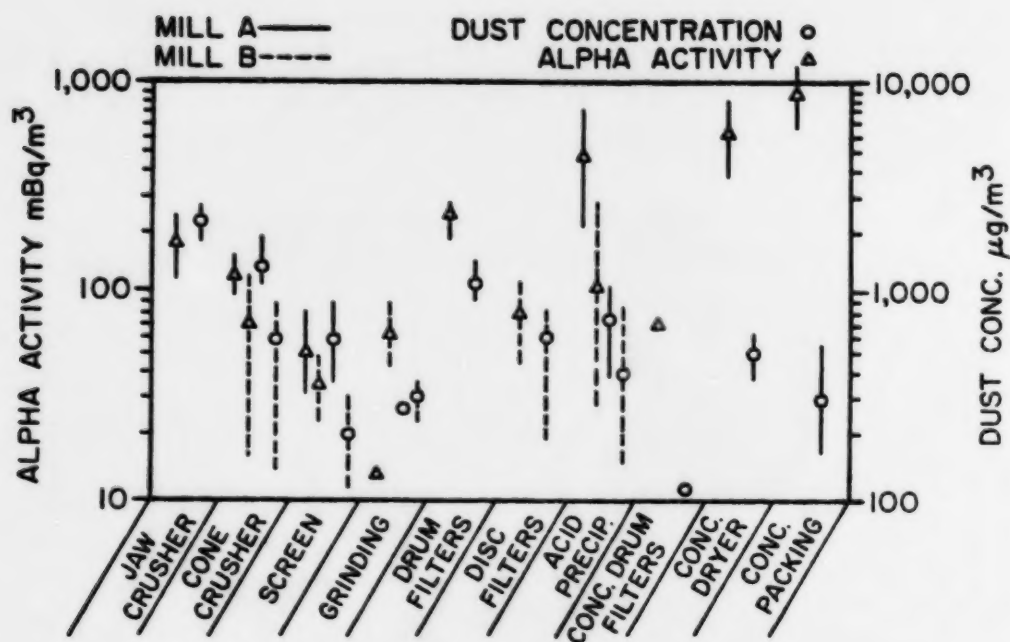


Fig. 6 Dust mass concentration and alpha activity concentration in mill locations. Note: Solid and dotted lines indicate the range of observed values.

4.2 Dust mass distribution

The Cascade impactor results for dust mass were plotted as outlined in section A-1-1. The mass distributions were generally straight lines on the log-gaussian probability graph paper, indicating a log-normal distribution of MMADS. The MMAD's and σ 's determined for the underground sample locations at mine A are shown on Fig. 7. The mean values of the MMAD's for the various locations range from 1 to 5 μ m aerodynamic diameter. The average corresponding σ value was about 10. This large dispersion indicates that a wide range of particle sizes was present in the airborne dust underground, likely because of the variability of dust sources during the sampling period.

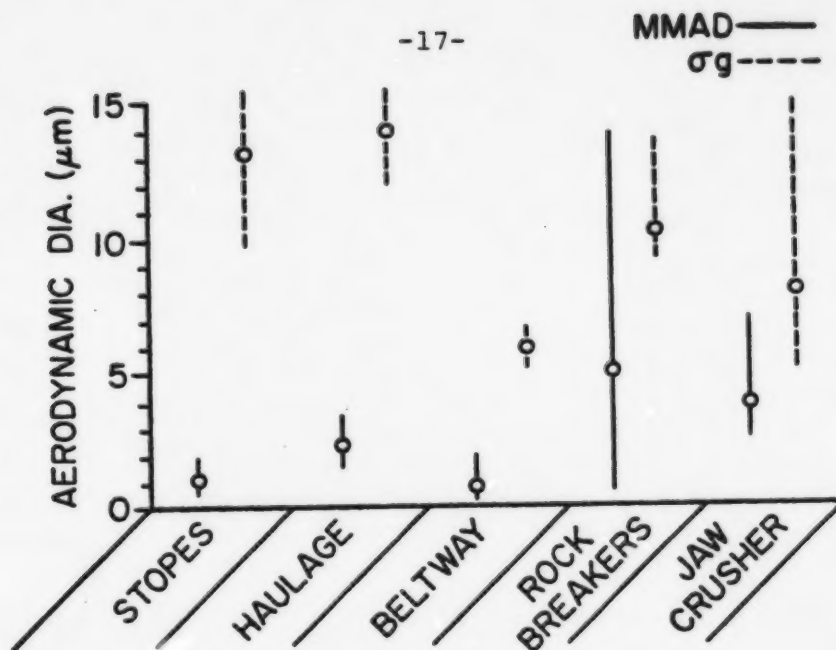


Fig. 7 Range of measured MMAD's for underground locations at Mine A.

4.3 Gross alpha activity distributions

From a radiation protection and regulatory viewpoint, only the AMADS are significant. The AMADS determined for the sample locations at mines A and B are shown on Fig. 8. The underground locations had AMAD's generally between 6 and 11 μm . The exceptions were haulage drifts which had AMADS greater than 20 μm . The corresponding σ_g values ranged from 3 to 5 with a mean of 4.3.

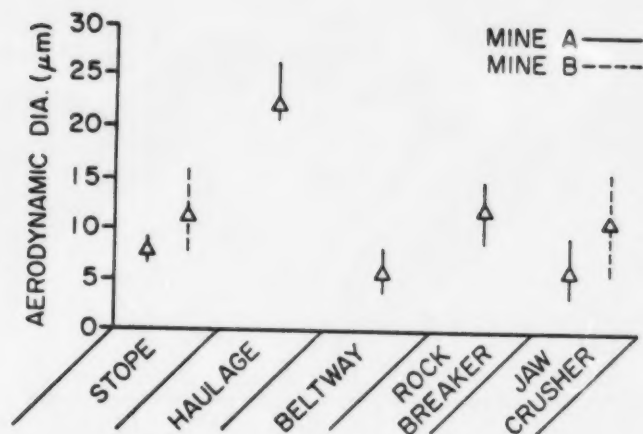


Fig. 8 AMAD's for underground locations at mine A and B

Fig 9 shows the AMADS determined for mill A and mill B locations. The AMADS ranged from 5 to 10 μm with the corresponding ag's ranging between 3 and 5.

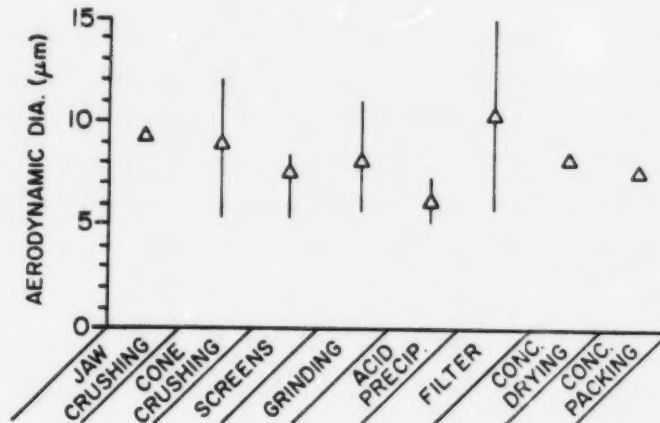


Fig 9. AMAD's for mill A and B combined

* Filters: include drum and disc dewatering filters before leaching

Note: Jaw crushing, conc. drying and concentrate packing are mill A only.

4.4 Alpha Spectra Analysis

Due to the overlapping of alpha energy peaks, each alpha emitter of the uranium and thorium decay series could not be identified by this method. Some of the different alpha emitters have similar alpha energies and therefore what appears like a single peak is actually combinations of several peaks of similar energies. The more distinct alpha energy peaks included U238, Rn222, Po218, Po216, Po214 and Po212.

4.4.1 Estimation of Radon and Thoron Gas Emanation from Ore Dust.

In this analysis we assumed the ratio of uranium and thorium in the ore dust was 2 to 1, which was the ratio found in the ore body generally. If secular equilibrium exists between all elements in the decay series the ratio of Po218 plus Po214 counts to the total alpha count must be 0.19.*

The alpha counts were measured for Po218 and Po214 and compared to the total alpha count. The ratio ranges from 0.10 to 0.22, with an average of about 0.15. (25% lower than the equilibrium ratio of 0.19). Therefore, the amount of radon that emanated from the ore particles ranges from 0 to 50%, with an average of 25%.

Under secular equilibrium the ratio of Po216 alpha activity to total alpha activity would be 0.018. Thoron emanation ranged from 6 to 55 percent with an average of about 25%. Table 4 shows results from 17 alpha spectra analysed for radon and thoron emanation.

* See tables 8,9 and 10 for the contribution of each radionuclide to the radioactivity of uranium ore.

Table 4: Radon and Thoron emanation rates from ore dust

SITE	DATE	Po218 + Po214 COUNT TOTAL ALPHA COUNT	RADON EMANATION IN (%)	Po216 COUNT TOTAL ALPHA COUNT	THORON EMANATION IN (%)
CRUSHER	05 04 82	0.18	14	0.011	39
"	05 05 82	0.22	0	0.013	28
"	11 01 82	0.18	14	0.017	6
ROCKBREAKER	05 07 82	0.10	50	0.015	17
"	11 03 82	0.18	14	0.016	11
"	01 27 83	0.15	29	0.013	28
HAULAGE	02 04 83	0.10	50	0.017	6
"	02 18 83	0.10	50	0.008	55
STOPES	03 08 83	0.14	33	0.012	33
"	11 22 82	0.19	10	0.010	44
BELTWAY	06 30 82	0.16	24	0.016	11
"	10 15 82	0.14	33	0.015	17
"	07 01 87	0.14	33	0.013	28

Analysis of data from cascade impactor samples has shown no measureable difference in radon and thoron emanation rates for the observed different particle sizes (the particle sizes ranged between 0.1 microns and 15 microns aerodynamic diameter).

4.5 Neutron activation analysis (N.A.A.)

The mass of U²³⁸ and Th²³² was measured by Neutron Activation Analysis on a subset of open face filters and Cascade Impactor substrates. Although there was good agreement in average between, Neutron Activation Analysis (NAA) data and measured gross alpha activity, wide discrepancies were observed on individual samples. These discrepancies could also be explained by a inhomogeneous micro distribution of U and Th oxides in the ore. Fig. 10 shows the range and number of cases for the ratio of measured alpha activity to the estimated alpha activity from (NAA) data.

NAA gave the mass of uranium²³⁸ on dust samples. By dividing the uranium mass by the collected dust mass the uranium grade of the ore dust was determined. For all samples analysed by NAA the ore grade was 0.08 percent uranium. The average ore grade at the mines sampled was about 0.1 percent. There is neither uranium depletion nor enrichment when mineral dust is generated by mining operations.

Cascade impactor data showed that ore grade decreased as the particle size decreased. This may be due to the presence of diesel exhaust which contributes to the mass collected on the lower stages but not to the alpha activity. This hypothesis was substantiated by analysing impactor data from the mills. The ore grades were consistent for all particle sizes where there was no influence from diesel particulates. The NAA data and comparisons are tabled in Appendix D.

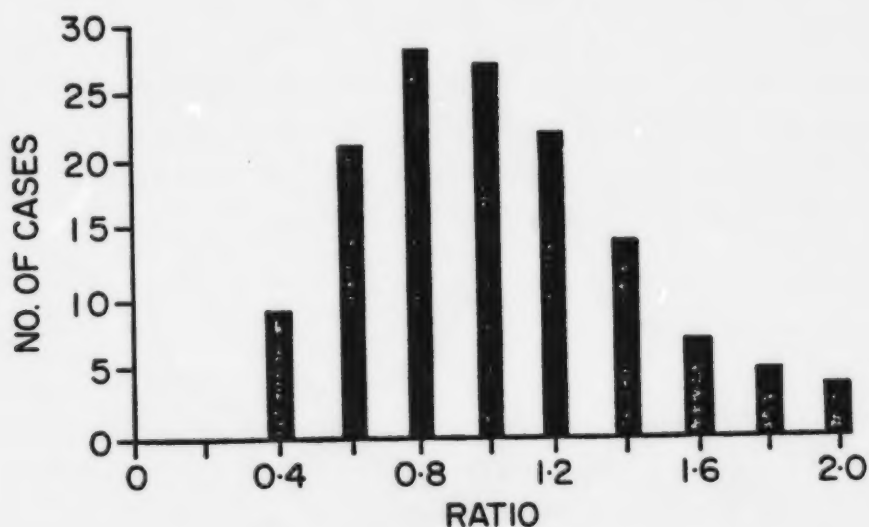


Fig. 10 R=Ratio of Measured Alpha Activity to theoretical Alpha Activity calculated from U and Th content as determined by Neutron Activation Analysis

B. DETERMINATION OF THE COMMITTED EFFECTIVE DOSE EQUIVALENT
INCURRED FROM EXPOSURE TO AIRBORNE LONG LIVED DUST

i. Basis for limiting occupational exposure to ionizing radiation.

In order to prevent the occurrence of non-stochastic health effects, the ICRP has set a dose equivalent limit of 0.5 Sv in a year to all tissues (except the lens of the eye). That limit applies irrespective of whether the tissues are exposed singly, or together with other organs.

For stochastic effects, the ICRP (1) recommends a system for limiting exposure based on the principle that the limit on risk should be equal whether the whole body is irradiated uniformly or non-uniformly. This condition is met if

$$\sum W_T H_T \leq H_{wb}$$

Where:

W_T is a weighting factor representing the stochastic risk resulting from tissue T to the total risk when the whole body is irradiated uniformly;

H_T is the dose equivalent received by tissue T;

H_{wb} is the stochastic dose equivalent limit for uniform irradiation of the whole body.

The ICRP recommends that for occupational exposure $H_{wb} \leq 50$ mSv per year. The values for W_T are given in Table 5.

Several organs and tissues will be irradiated following the entry of a radionuclide into the body. In any year of practice, the

dose accumulated over the 50 years following the intake (H_{50}) in all the organs of the body must be limited so that the resulting total risk of cancer and hereditary disease is less than, or equal to, the risk from irradiating the whole body uniformly to the appropriate annual dose-equivalent limit of 50 mSv. In other words, the risk to health arising from exposure to a combination of radiation hazards (external irradiation, ingestion and inhalation of various radionuclides) must not exceed the risk arising from the exposure to the Dose-Equivalent Limit of a single radiation hazard.

Therefore, in order to meet the ICRP's basic limits for the exposure of workers, the intake of radioactive materials in any year must be limited to simultaneously satisfy the following conditions (primary limits):

$$\sum w_T H_{50,T} < 0.05 \text{ Sv}$$

$$\text{and } H_{50,T} < 0.5 \text{ Sv}$$

Where w_T is the weighting factor shown in Table 5

Table 5: Weighting factors recommended by the Commission for stochastic risks

Organ or Tissue	w_T
Gonads	0.25
Breast	0.15
Red bone marrow	0.12
Lung	0.12
Thyroid	0.03
Bone Surfaces	0.03
Remainder	0.30

2. Secondary and derived limits for the control of internal dose

With the exception of the uniform irradiation of the whole body by penetrating ionizing radiation, it is generally impossible to measure directly the dose received by workers exposed to various radiation hazards, especially those generated by airborne radioactive particulate materials.

In that case, the Committed Effective Dose Equivalents (H_{50}) for concerned target tissues are estimated by the method described in section B.3.

2.1 Annual Limit on Intake (ALI)

The Annual Limit on Intake (ALI) of a radionuclide is a secondary limit designed to meet the basic limits for occupational exposure recommended by the Commission, and is derived as follows. The ALI is the greatest value of annual intake (I) which satisfies both of the following inequalities

$$I \sum w_T (H_{50,T} \text{ per unit intake}) < 0.05 \text{ Sv} \quad (4)$$

$$I (H_{50,T} \text{ per unit intake}) < 0.5 \text{ Sv} \quad (5)$$

Where:

I (Bq) is the annual intake of the specified radionuclide either by ingestion or inhalation

w_T is the weighting factor for tissue T

$H_{50,T}$ per unit intake (in Sv.Bq^{-1}) is the committed dose equivalent in tissue (T), from the intake of unit activity of the radionuclide by the specified route.

2.2 Derived Air Concentration (DAC)*

The DAC for any radionuclide is defined as that concentration in air (Bq. m^{-3}) which, if breathed by Reference Man(2) for a working year of 2000 hours (50 weeks at 40 h per week) under conditions of "light activity"**, would result in the ALI by inhalation.

$$\begin{aligned} \text{DAC} &= \text{ALI} / (2000 \times 60 \times 0.02) \\ &= \text{ALI} / 2.4 \times 10^3 \text{ Bq.m}^{-3} \end{aligned}$$

where 0.02 m^3 is the volume of air breathed at work by Reference Man per minute under conditions of light activity.

* The ICRP 30 Publication emphasizes that the ALI is the overriding limit and the DAC should always be used circumspectly

** The ICRP 30 Publication does not indicate whether a miner's activity fits the definition of "light activity"

3. Methodology for determining the Committed Effective Dose Equivalent

In the present work, ALI's and DAC's were calculated according to the dosimetric model for the respiratory system described in the ICRP Publication 30 (Appendix F)

In the case of uranium mines and mills, the Committed Effective Dose Equivalent (H_{50}) ensuing the exposure to airborne uranium ore dust or uranium concentrates is influenced by the physical and chemical characteristics of the contaminants, namely the size distribution parameters (Activity Median Aerodynamic Diameter and Geometric Standard Deviation), and the radionuclide biological half-life of the various radionuclides.

The process used to determine the ALI and DAC for uranium ore dust and uranium concentrates follows the steps listed below:

- determination of the AMAD of the aerosol
- determination of the radionuclide make-up of the aerosol
- determination of the ALI for each individual radionuclide, assuming an AMAD of 1 μm
- determination of the deposition and retention rate of the aerosol in the respiratory tract for AMAD's different from 1 μm
- determination of the Committed Effective Dose Equivalent ($H_{50,T}$ per unit intake) for each radionuclide and each target organ, for the range of AMAD corresponding to a given facility, or part of the facility.
- determination of the ALI for the actual mixture and size distribution of radionuclides

Airborne uranium ore dust contains all the radionuclides of the U-238, U-235 and Th-230 decay series.

From the data provided in the ICRP publication 30, the values for the fraction f_{N-P} , f_{T-B} , f_p of the Committed Effective Dose Equivalent in the target tissues resulting from the deposition in the N-P, T-B and P regions were used to calculate the particle size correction, according to the equation

$$\frac{H_{50}(AMAD)}{H_{50}(1\mu m)} = f_{N-P} \frac{D_{N-P}(AMAD)}{D_{N-P}(1\mu m)} + f_{T-B} \frac{D_{T-B}(AMAD)}{D_{T-B}(1\mu m)} + f_p \frac{D_p(AMAD)}{D_p(1\mu m)}$$

The values for D_{N-P} , D_{T-B} , and D_p were determined from Table 6 and Figure 5.1 in Appendix E

Diameter	D_{N-P}	D_{T-B}	D_p
1 μm	0.32	0.07	0.25
2 μm	0.50	0.07	0.17
5 μm	0.75	0.07	0.08
10 μm	0.88	0.07	0.05

Table 6: Deposition fractions of aerosols in the Naso-Pharynx (D_{N-P}), Tracheo-Bronchial (D_{T-B}), and Pulmonary (D_p) regions of the respiratory tract.

3.1 Radiological characteristics of Elliot Lake ore

Although this may not be absolutely true, in the absence of precise information, it is assumed in the course of this work that in the U-238 decay series, the first decay products (Th-234, Pa-234, U-234, Th-230, Ra-226) are in equilibrium with U-238, and in the U-235 decay series, Th-231, Pa-231, Ac-227, Th-227 and Ra-223 are in equilibrium with U-235. In the Th-232 decay series, Ra-228, Ac-228, Th-228, and Ra-224 are in equilibrium with Th-232.

A standard Uranium and Thorium content has been assumed for the Elliot Lake ore, as given in Table 7.

Table 7: Characteristics of the Elliot Lake Uranium Ore.
(in g of U per g of ore).

Uranium 238 content: 1000 ppm = 10^{-3}g.g^{-1} = 12.34 Bq.g ⁻¹
Uranium 235 content: 70 ppm = 7.10^{-5}g.g^{-1} = 0.554 Bq.g ⁻¹
Thorium 232 content: 500 ppm = 5.10^{-4}g.g^{-1} = 2.06 Bq.g ⁻¹

The specific mass activity of every radionuclide present in uranium ore dust (Bq.g⁻¹) in the Elliot Lake mines is given in tables 7, 8, 9, 10. Table 11 summarizes tables 7 to 10. Two cases have been considered:

- a) secular equilibrium is achieved between all the elements of the decay series and
- b) there is a radioactive disequilibrium caused by the escape of Radon and Thoron gas from dust particles.

Due to its very short half life (3.92 s), the emanation rate of Rn-219 (U-235 decay series) is assumed to be negligible. Tables 8 to 11b, indicate for what radionuclides there is an ALI, along with the type of nuclear emission and the relative contribution (in %) to the total radioactivity associated with an ALI.

Table 8: U-238 decay series assuming Rn-222 emanation rate of 30%.

Radio- nuclide	Emission	Activity sec.equil Bq.g ⁻¹	Activity E.L.equil Bq.g ⁻¹	ALI	% "ALI" activity sec.equil	% "ALI" activity E.L.equil
U 238	α	12.33	12.33	x	8.23	9.39
Th234	β	"	"	x	"	"
Pa234	β	"	"	x	"	"
U 234	α	"	"	x	"	"
Th230	α	"	"	x	"	"
Ra226	α	"	"	x	"	"
Rn222	α	"	8.63	-	-	-
Po218	α	"	"	-	-	-
Pb214	β	"	"	x	"	6.5/
Bi214	β	"	"	x	"	"
Po214	α	"	"	-	-	-
Pb210	β	"	"	x	"	"
Bi210	β	"	"	x	"	"
Po210	α	"	"	x	"	"
Total	18 α	98.67	83.87			
	16 β	74.00	59.20			
Total		172.67	143.07			

Specific mass activity for 1 g of Elliot Lake ore.

Table 9: U-235 decay series - Emanation rate of Rn-219 of 0%

Radio- nuclide	Emission	Activity sec.equil Bq.g-1	Activity E.L.equil Bq.g-1	ALI	% "ALI" activity sec.equil	% "ALI" activity E.L.equil
U 235	α	0.5546	0.5546	x	0.37%	0.42%
Th 231	β	"	"	x	"	"
Pa 231	α	"	"	x	"	"
Ac 227	β	"	"	x	"	"
Th 227	α	"	"	x	"	"
Ra 223	α	"	"	x	"	"
Rn 219	α	"	"		-	-
Po 215	α	"	"		-	-
Pb 211	β	"	"	x	"	"
Bi 211	α	"	"		-	-
Tl 207	α	"	"		-	-
Total	8 α	4.44	4.44			
acti.	3 β	1.66	1.66			
Total		6.10	6.10			

Specific mass activity for 1 g of Elliot Lake ore

Table 10: Th-232 decay series

Radio- nuclide	Emission	Activity sec.equil Bq.g ⁻¹	Activity E.L.equil Bq.g ⁻¹	ALI	% "ALI" activity sec.equil	% "ALI" activity E.L.equil
Th 232	α	2.06	2.06	x	1.373	1.57
Ra 228	β	"	"	x	"	1.57
Ac 228	β	"	"		-	-
Th 228	α	"	"	x	"	"
Ra 224	α	"	"	x	"	"
Rn 220	α	"	"		-	-
Po 216	α	"	"		-	-
Pb 212	β	"	"		-	-
Bi 212	α, β	"	"	x	"	"
Po 212	α, β^+	1.373	1.373		-	-
Tl 208	α	0.687	0.687		-	-
Total	$\alpha = 6$	12.36				
Act.	$\beta = 4$	8.24				
Total		20.60				

Specific mass activity for 1 gram of Elliot Lake ore

Table 11a: Summary of tables 8,9 and 10 for radionuclides with an ALI. Specific mass activities in Bq per gram of ore for each decay series.

Decay Series	Secular equilibrium radioactivity per gram of ore (Bq.g ⁻¹)			Elliot Lake equili. radioactivity per gram of ore (Bq.g ⁻¹)		
	Bq ALI Alpha	Bq ALI Beta	Bq ALI Total	Bq ALI Alpha	Bq ALI Beta	Bq ALI Total
U238	61.67	74.00	135.67	57.97	59.20	117.17
U235	2.22	1.66	3.88	2.22	1.66	3.88
Th232	6.87	3.43	10.30	6.87	3.43	10.30
Total	70.76	79.09	149.85	67.06	64.29	131.35

Table 11b: Summary of Tables 8,9 and 10 for α activity only.

	Specific Mass Activity	
	Secular Equilibrium (Bq.g ⁻¹)	Elliot Lake Equilibrium (Bq.g ⁻¹)
U238 series	115.47	100.67
U235 series	4.44	4.44
Th232 series	12.36	12.36

3.2 Determination of the ALI for a mixture of radionuclides

The general equation used for calculating the ALI and for a mixture of radionuclides is:

$$\frac{I}{\text{ALI mixture}} = \sum_i \frac{K_i}{\text{ALI}_i}$$

Where

ALI mixture is the ALI for the actual mixture of radionuclides found in the air.

ALI_i is the ALI for the radionuclide i alone.

K_i is the relative contribution of the radionuclide i to the global activity of the mixture.

The calculation of the ALI for actual uranium ore dust is made according to the equations given in the ICRP 30 Publication. Although all the radionuclides contribute to the global radioactivity of the dust, not all of them are attributed a H_{50,T} value (in other words, not all of them deliver a significant dose to the body). That is the case for Rn-219, Po-215, Pb-211 and Bi-211 in the U-235 decay series, Rn-222, Po-218, Po-214 in the U-238 decay series, and of Ac-228, Rn-220, Po-216, Pb-212, Po-212 and Tl-208 in the Th-232 decay series.

ALI's for each radionuclide of concern (those for which there is an ALI) have been calculated from H_{50,T} values given in the ICRP 30 Publication. The following notation has been used for each radionuclide:

ALI(NS): Annual Limit on Intake for non-stochastic effects

$$ALI(NS) = \frac{0.5}{H_{50,T}}$$

ALI(S) Annual Limit on Intake for stochastic effects

$$ALI(S) = \sum \frac{0.05}{W_T H_{50,T}}$$

Table 12: ALI values for whole body dose, for the radionuclides of the U-238, U-235, and Th-232 series, for AMAD of 1,2,5 and 10 microns, and their relative contribution to total activity.

AMAD microns	1	2	5	10	% contribution to activity	
Radio- nuclide	ALI(wb)(in Bq)				Secular equil.	E.L. equil
U 238	1543	2264	4823	7716	8.23	9.39
Th 234	5.63.10 ⁶	7.32.10 ⁶	1.11.10 ⁷	1.31.10 ⁷	"	"
Pa 234	2.48.10 ⁸	2.45.10 ⁸	2.32.10 ⁸	2.2.10 ⁸	"	"
U 234	1389	2042	4340	6944	"	"
Th 230	575	778	1264	1558	"	9.39
Ra 226	2.33.10 ⁴	3.22.10 ⁴	5.57.10 ⁴	7.15.10 ⁴	"	6.57
Pb 214	2.78.10 ⁷	3.93.10 ⁷	7.28.10 ⁷	1.01.10 ⁸	"	"
Bi 214	3.2.10 ⁷	4.71.10 ⁷	10 ⁸	1.6.10 ⁸	"	"
Pb 210	6950	6646	6040	5614	"	"
Bi 210	9.65.10 ⁵	1.43.10 ⁶	3.02.10 ⁶	4.85.10 ⁶	"	"
Po 210	2.28.10 ⁴	2.84.10 ⁴	3.83.10 ⁴	4.21.10 ⁴	"	"
U 235	1490	2190	4650	7440	0.37	0.423
Tn 231	2.15.10 ⁸	2.33.10 ⁸	2.22.10 ⁸	2.09.10 ⁸	"	"
Pa 231	139	186	292	352	"	"
Ac 227	149	209	348	415	"	"
Th 227	1.16.10 ⁴	1.7.10 ⁴	3.62.10 ⁴	5.79.10 ⁴	"	"
Ra 223	2.45.10 ⁴	3.59.10 ⁴	7.49.10 ⁴	1.18.10 ⁵	"	"
Pb 211	2.52.10 ⁷	3.23.10 ⁷	5.77.10 ⁷	7.77.10 ⁷	"	"
Th 232	100	135	219	271	1.373	1.57
Ra 228	4.36.10 ⁴	5.53.10 ⁴	7.72.10 ⁴	8.64.10 ⁴	"	"
Th 228	604	888	1895	3019	"	"
Ra 224	6.31.10 ⁴	9.24.10 ⁴	1.93.10 ⁴	3.04.10 ⁵	"	"
Bi 212	1.07.10 ⁷	1.47.10 ⁷	2.57.10 ⁷	3.42.10 ⁷	"	"

For each radionuclide and each AMAD value, the ALI values used for radiation protection and regulatory purposes are the lowest of $ALI_{(S)}$ and $ALI_{(NS)}$ values.

From the acceptable ALI values, the global ALI for the actual mixture of radionuclide, as defined in Table (10, 11, 12) were calculated, according to the equation (8) of section 3.2.

Two cases have been investigated:

- all radionuclides are in secular equilibrium
- there is a radioactive disequilibrium due to the escape of Radon gas from the ore and from dust particles.

Table 12 summarizes ALI values for all the radionuclides present in the U-238, U-235 and Th-232 decay series. Detailed calculations of ALI are given in Appendix E.

3.3 Errors introduced in neglecting radionuclides with high ALI

The radionuclides that have high ALI contribute less to the Committed Effective Dose Equivalent than those with a low ALI. It is possible to evaluate the error that would be introduced by neglecting the radionuclides that contribute less to the final dose.

For ANAD = 1 micron, ALI's range from 100 Bq for Th-232 to $2.48 \cdot 10^8$ for Pa-234. Within that range, 9 radionuclides have an ALI lower than 10^4 Bq and 14 have an ALI larger than 10^4 Bq. (Table 13).

Systematic errors introduced in ALI values by neglecting the radionuclides having an ALI greater than 10^4 Bq are shown in Table 14.

Table 13: Radionuclides with an ALI greater than 10^4 Bq and 10^5 Bq (AMAD of 1 micron).

Radionuclide	ALI(Bq)	ALI<104Bq	ALI>105Bq
U 238	1543		
Th 234	$5.63 \cdot 10^6$	x	x
Pa 234	$2.48 \cdot 10^8$	x	x
U 234	1389		
Th 230	579		
Ra 226	$2.33 \cdot 10^4$	x	
Pb 214	$2.78 \cdot 10^7$	x	x
Bi 214	$3.2 \cdot 10^7$	x	x
Pb 210	6950		
Bi 210	$9.65 \cdot 10^5$	x	x
Po 210	$2.28 \cdot 10^4$	x	
U 234	1490		
Tn 231	$2.15 \cdot 10^8$	x	x
Pa 231	139		
Ac 227	149		
Th 227	$1.16 \cdot 10^4$	x	
Ra 227	$2.45 \cdot 10^4$	x	
Pb 211	$2.32 \cdot 10^7$	x	x
Th 232	100		
Ra 228	$4.36 \cdot 10^4$	x	
Th 228	604		
Ra 224	$6.31 \cdot 10^4$	x	
Bi 212	$1.07 \cdot 10^7$	x	x

Table 14: Overestimation of "ALI mixture" introduced by neglecting radionuclides with an ALI value greater than 10^4 Bq.

AMAD (microns)	ALI overestimated by	
	Secular Equilibrium	Elliot Lake Ore Equilibrium
1	1.7%	2.1%
2	1.7%	1.5%
5	1.9%	1.5%
10	2.%	1.6%

4 Derived Air Concentration of uranium ore dust in air.

Tables 15 and 16 indicate the derived air concentration of a mixture of radionuclides, calculated from the equation:

$$DAC = ALI/2400$$

where

DAC is the activity air concentration of the radioactive contaminants in $Bq.m^{-3}$

ALI is the annual limit on intake, in Bq

and 2400 is the total volume of air in m^3 , breathed by the Standard Man over the standard working year (breathing rate of $1.2 m^3.h^{-1}$ during 2000 hours).

Table 15: ALI values for Elliot Lake ore in Bq (alpha + beta)

AMAD				
(microns)	1	2	5	10
Secular equilibrium	2070	2750	4670	5900
Elliot Lake equilibrium	1830	2500	4240	5400

TABLE 16: DAC values for Elliot Lake ore in mBq.m⁻³ (alpha + beta)

AMAD				
(microns)	1	2	5	10
Secular equilibrium	860	1150	1950	2460
Elliot Lake equilibrium	760	1040	1770	2250

5. DAC and practical aspects of monitoring long-lived uranium dust concentration in air.

5.1 Measurement techniques

It is of interest to note that the notion of "respirable dust" does not apply in the case of radioactive material, because of the contribution of the dust fraction deposited in the Naso-Pharynx and tracheo-bronchial regions which contribute to the total Committed Effective Dose Equivalent.

With respect to monitoring the concentration of long-lived radionuclides in the air, only two general methods are available.

In the first method, a known volume of air is sampled through a filter, and the mass of airborne material collected on the filter is measured. Workers' exposures can be calculated from their occupancy time, the dust concentration in air measured at the relevant working places and the uranium concentration in the dust.

In the second method, the radioactivity of the particulate material collected on the filter is measured by means of the appropriate radiation counters. Filters can be counted for alpha, beta or gamma radiation or any combination of them.

However, for radiation protection purposes, the most convenient and economical is alpha radiation counting. When the number of samples is sufficient, the more sophisticated simultaneous alpha-beta counting can be envisaged.

The first method can be used when uranium dust only is present in the air, and if the uranium concentration in dust is constant over very long periods of time. Whenever those conditions are

not met, the measured mass of airborne material will not give reliable information on the radiation exposure received by the workers. Since there are very few cases, if any, where only pure uranium is present in the atmosphere, the second method (radiation counting) is the most reliable way of measuring the concentration of uranium-bearing material in air.

On the one hand, in uranium mines and mills, as indicated in Part 1, the air concentration of alpha-emitting material is low, in the range of 20 to 1000 mBq.m⁻³. On the other hand, alpha radiation counters always have a background counting rate, however low, which is never nil. Therefore, when alpha-radiation counting techniques are used, the volume of air sampled through a filter must be sufficient to provide a counting rate which is distinguishable from the background. In practice, a volume of about 1 m³ is appropriate. If an automatic sample counter is used, it is advisable to insert into the batch of samples a calibration source and two blank planchets with unused filters, in order to check systematically the counting efficiency and the background of the alpha counter. The counting time must also be set to obtain large enough counts, in order to reduce the statistical errors attached to low counts.

5.2 DAC for global radioactivity and DAC "alpha"

ALI's values calculated in section 3 and summarized in table 12 are given in Bq. The activity which is referred to is the radioactivity emitted by the radionuclides of concern in radiation protection, that is those for which there is an ALI. However, in the ore as in the airborne ore dust, all the radionuclides from U-238, U-235 and Th-232 decay series are present, and all contribute to the activity emitted, in proportion to their relative abundance. Not all of them have an ALI. Therefore, it is necessary to translate the DAC values

(derived from ALI values) calculated for a given facility, or part of a facility, into the DAC "alpha" which is representative of the radiation emitting material that will actually be "seen" by the radiation counter.

To that effect, the contribution of each radionuclide present in the "Standard Elliot Lake Ore" to the activity has been determined and is given in Table 12. This contribution is given in percent of the total radioactivity emitted by an uranium ore that contains twice as much uranium as thorium, and for which two cases were considered.

Case 1: no radon escapes from dust particles
(secular equilibrium)

Case 2: 30% of the radon produced in the ore dust particles escapes to the atmosphere
(Elliot Lake equilibrium)

Although part of the thoron gas escapes to the atmosphere, an emanation rate of 0% for thoron gas has been used in the determination of the Elliot Lake ore equilibrium, because of the little influence this phenomenon has on the determination of ALI's and DAC values.

The distribution of the total activity emitted by the uranium ore dust can be represented according to Table 17.

Table 17: Total activity, "ALI" activity, "non-ALI" activity, alpha activity and beta activity in uranium ore dust

Total Activity emitted by the uranium ore particles			

Beta activity	Alpha activity	Alpha activity	Beta activity
emitted by	emitted by	emitted by	emitted by
radionuclides	radionuclides	radionuclides	radionuclides
WITHOUT ALI	WITHOUT ALI	WITH ALI	WITH ALI
-----	-----	-----	-----
		"ALI" activity	

	measured alpha activity		

In the case of the Elliot Lake ore, at secular equilibrium, the ratio of the total alpha activity measured to the "ALI" activity is:

$$\frac{132.27}{149.85} = 0.88$$

under the "Elliot Lake equilibrium", this ratio becomes:

$$\frac{117.47}{131.35} = 0.89$$

In other words, about 90 alpha emissions correspond to 100 nuclear emissions (alpha and beta) emitted by radionuclides with an ALI.

For radiation protection purposes, the measured ALI and DAC values must be multiplied by 0.90 to determine the ALI and DAC values that are measured in practice.

TABLE 18: ALI and DAC values for Elliot Lake ore in mBq.m⁻³ (alpha activity only, rounded values)

ANAD	1	2	5	10	
(microns)					
Secular	1860	2480	4200	5300	ALI(α)
					Bq
equilibrium	770	1000	1800	2200	DAC(α)
					mBq.m ⁻³
Elliot Lake	1650	2250	3800	4900	ALI(α)
					Bq
equilibrium	700	900	1600	2000	DAC(α)
					mBq.m ⁻³

5.3 Other approaches for determining ALI values.

5.3.1 NRPB approach

The National Radiological Protection Board of the United Kingdom, in the NRPB-82 publication (Ref. 3) has calculated the ALI and DAC values for 169 radionuclides, according to the ICRP 30 recommendations. The discrepancy in ALI's for Pa-231 is due to the fact the NRPB-82 has used metabolic data different from those used in ICRP 30. However, due to the small contribution of the U-235 decay series to the radioactivity of the ore, the difference in ALI(mixture) is negligible in practice.

5.3.2 Hannibal's approach

Hannibal (Ref. 4) has also calculated the ALI and DAC values for every radionuclide of the U-238, U-235 and Th-232 decay series. His DAC are expressed in terms of mg of ore dust per m³ of air.

For comparison purposes, Hannibal's ALI and DAC values have been translated into Bq.m⁻³, for the radiological composition of the Elliot Lake ore. Hannibal took a more restrictive approach than ICRP 30 regarding the solubility class of the concerned radionuclides by using systematically class Y for all radionuclides. On the other hand, Hannibal uses only ALI (stochastic) for all radionuclides, thereby increasing the ALI(mixture) relatively to those calculated in that report, where the lowest of the ALI_S (stochastic) and ALI_{NS} (non-stochastic) are used to determine the ALI mixture. However, these discrepancies in methodology do not lead to significantly different ALI and DAC values for the Elliot Lake ore. The only shortcoming of Hannibal's work is that he expresses DAC's in milligrams of dust per cubic meter of air, which is not a convenient unit in the case of mine atmospheres, because uranium ore dust is not the only constituent of the aerosol, and the uranium/thorium content in the dust may be highly variable.

5.3.3 Johnson's approach

Johnson (Ref. 5) investigated the influence of several dosimetric and metabolic models on the determination of ALI and DAC. His assumptions are given below, and the ALI and DAC calculated values are given in Tables 19 and 20.

Case 1

All radionuclides are assumed to be Class Y, and have an $f_1 = 0.0002$ as ore dust is assumed to be fairly insoluble. Provided f_1 is small, uncertainties in f_1 do not impact on the dose.

Case 2

There is evidence that the ICRP clearance model over-predicts the amount of activity cleared to the blood directly from the P region of the lung for insoluble compounds. The ICRP clearance to blood of 5% of the deposited activity was reduced to 1%, and that to the GI tract (long term) was increased to 44%. All other parameters are unchanged. Case 1 modifications are maintained.

Case 3

The ICRP clearance model also has 13.5% of the activity deposited in the P region being cleared to blood via lymph nodes. This fraction may be appropriate for very small particles, or those that are slightly soluble, but is probably too large for large insoluble particles. Case 3 gives the results for the percent cleared to blood via lymph nodes set to 2%, and that cleared to lymph nodes that stays there indefinitely changed from 1.5% to 2%. The changes made in Cases 1 and 2 remain.

Case 4

The ICRP model assumes that any thorium going to the skeleton is retained on bone surfaces with a half-life of 8000 days. Case 4 gives the results of calculations assuming that the thorium going to the skeleton is uniformly distributed in mineral bone. The modifications used in Case 3 are retained.

Case 5

Case 5 is the same as Case 4 except the alpha activity in lymph nodes, which is not thought to have a significant contribution to the risk of lung cancer, is not included in calculating the lung dose.

Case 6

Case 6 is identical to Case 5 except the regional lung concept, rather than the composite one, is used.

Table 19 summarizes the ALI values calculated by Johnson according to the ICRP 30 recommendations and the assumptions made in case 1 to 6. The lowest of ALI_S and ALI_N values are taken. The Elliot Lake ore values are calculated assuming that the uranium series and the thorium series contribute for 91.8% and 8.2% to the "ALI" activity respectively.

Table 19: ALI values calculated by Johnson, and ALI values for the Elliot Lake ore, according to the assumptions indicated in section 5.3.3.

	ALI (alpha + beta)						
	Johnson's case no.						
	ICRP	1	2	3	4	5	6
U dust	2300	1600	1700	2000	2200	3900	6800
Th	570	570	670	1000	1400	2000	2600
E.L.							
Ore	1840	1400	1500	1850	2100	3620	6000

The ALI values calculated by NRPB, Hannibal, Johnson, are presented in Table 20 along with the values given in the present report.

5.3.4 Jammet's interpretation of ICRP 30 Publication

Jammet (6) applied the ICRP 30 Publication recommendations to the particular case of uranium mines. The ALI values he calculated are presented in Table 20.

5.3.5 Comparison of ALI values from the different authors

From Table 20, it can be seen that in general there is a good agreement between ALI values for the Elliot Lake ore dust calculated by five authors. Large discrepancies appear in Johnson's ALI calculations for cases 5 and 6 where different metabolic patterns are assumed (lymph nodes neglected as a target organ in case 5 and use of regional lung concept in case 6). In the absence of epidemiological or experimental proof of superiority of a metabolic or dosimetric model over the others, it seems reasonable to base radiation protection actions on the ICRP model.

Table 20: Comparison of ALI values for the Elliot Lake ore dust, (AMAD = 1 μ m, secular equilibrium).

Radio-nuclide	ALI (Bq) (alpha + beta) in Bq, AMAD = 1 μ m									
	This Work	NRPB 82	Hanni-bal	Johnson						JAMMET
				1	2	3	4	5	6	
Th 232	100	100	163							
Th 228	604	600	600							
U 235	1490	2000	1510							
Pa 231	139	50*	144							
Ac 227	149	200	142							
U 238	1543	2000	1560							2000
U 234	1389	1000	1390							1000
Th 230	575	600	720							600
Pb 210	6950	7000	3600							7000
E.L. ore										
(sec. equil.)	2070	1970	2520	1450	1520	1950	2160	3670	6730	
E.L. ore										
(E.L. equil.)	1830	1620	2080							

* Metabolic data different from those used in ICRP 30

6. ALI and DAC for Long Lived Dust in uranium concentrate area of uranium mills

From the acid precipitation area to the yellow cake packing area of an uranium mill, only the isotopes of uranium (U-238, U-234, U-235) are present in the solutions being processed, and in the final product. Therefore these operations will generate only uranium-bearing airborne materials. All the other radionuclides remain in the slurries that are directed towards the tailing piles.

The contribution of each isotope of uranium will contribute to the alpha activity of the dust as follows. At the secular equilibrium, the activity of U-234 equals that of U-238, and the activity of U-235 (0.7% in mass) is 4.5% of that of U-238.

The contribution of U-238 and U-234 to the total alpha activity of uranium concentrates are respectively:

$$\frac{1}{1 + 1 + 0.045} = 0.489$$

and that of U-235 is

$$\frac{0.045}{1 + 1 + 0.045} = 0.022$$

In part 1 of this report, it has been found that the AMAD value that is representative of long-lived aerosols in mills is 7 microns. The ALI values for U-238, U-235 and U-234 for an AMAD of 7 microns have been extrapolated linearly from the ALI values for AMADs of 5 and 10 microns.

$$\text{ALI (U-238, 7 microns)} = 5980 \text{ Bq}$$

$$\text{ALI (U-235, 7 microns)} = 5770 \text{ Bq}$$

$$\text{ALI (U-234, 7 microns)} = 5380 \text{ Bq}$$

Therefore the ALI for uranium concentrates (ALIconc) in mills is given by:

$$\frac{1}{\text{ALIconc}} = \frac{0.489}{5980} + \frac{0.489}{5380} + \frac{0.022}{5770}$$

$$\text{ALIconc} = 5670 \text{ Bq}$$

The corresponding DAC (concentrate) is:

$$\text{DAC(conc)} = \frac{5670}{2400} = 2360 \text{ mBq.m}^{-3}$$

Since the three radionuclides are alpha emitters, the DAC conc is directly usable for monitoring purposes. This is a DAC (alpha).

C. CONCLUSIONS

The physical characteristics of the airborne alpha emitting long-lived aerosols in the Elliot Lake mines and mills have been determined. Two main groups of radioactive long-lived aerosols have to be considered.

- aerosols in which all the radionuclides of U-238, U-235 and Th-232 decay series are present. These types of aerosols are present throughout the mines, and at the ore preparation areas of the mills (crushing, grinding).

- aerosols in which only the isotopes of uranium are present (U-238, U-234, U-235). These types of aerosols are present only in the mills, from the acid precipitation areas to uranium concentrate packing areas.

1. Underground locations

Due to the extreme variety of dust generating operations that take place in a mine, the range of AMAD of radioactive dust found in the mine atmosphere is quite wide. It seems reasonable to suggest that the arithmetic mean of the AMAD's measured at a representative workplaces be used for determining the corresponding Annual Limits on Intake for the radiation hazard of concern.

It is then suggested that the following values be considered for ALI and DAC determination:

underground stopes :	AMAD = 5 microns
haulage ways :	AMAD = 10 microns
Underground crushers and rockbreakers:	AMAD = 7 microns

Taking into account the specific radioactive disequilibrium that exists in the Elliot Lake ore, the corresponding ALI's and DAC's for these typical underground locations would respectively be as follows:

Stopes :	DAC	(α) = 1650 mBq.m ⁻³
Haulage ways :	DAC	(α) = 2000 mBq.m ⁻³
Underground crushers and rockbreakers :	DAC	(α) = 1800 mBq.m ⁻³

These suggested values are the best approximation that can be drawn from a large number of samples and analysis. However, as pointed out in the body of the report, variations do occur in time and place in the mine atmosphere, and no measurement limited in time and place can account for the actual quantity and characteristics of uranium ore dust to which the workers are exposed. Only continuous personal monitors can be used to measure that exposure.

2. Surface locations

2.1 Ore preparation areas in the mill

In those areas, as in underground locations, all the radionuclides present in the ore are also present in the airborne uranium ore dust, but since the sources of dust are less diversified than in the mine, the spread of AMAD is narrower than underground. In these areas (crushing, grinding), an average AMAD of 7 microns can be used for determining ALI(α) and DAC(α) values. The corresponding ALI and DAC values are respectively 4300 Bq and 1800 Bq.m⁻³.

2.2 Uranium concentrate areas

From the acid precipitation area to the uranium concentrate area, only the isotopes of uranium (U-238, U-235, U-234) are present in the solutions that are being processed and transformed into yellow cake. All the other radionuclides remain in the slurries that are discharged towards the tailings piles.

In these areas, due to the limited number of sources of aerosols, the observed AMAD's of radioactive airborne particles are relatively constant, with an arithmetic mean of about 7 microns. The corresponding ALI (alpha) and DAC (alpha) are respectively 5670 Bq and 2.36 Bq.m⁻³.

3. General considerations

In the absence of either epidemiological or experimental evidence of the superiority of one metabolic or dosimetric model over the others, it is delicate to recommend a particular ALI or DAC for uranium ore dust or uranium compounds in uranium mills. However, it is reasonable to base dust exposure evaluations on the the ICRP models that are widely known and accepted. Furthermore, it would be beneficial to the quality of future radiation protection in mines and mills to record exposures to specific radiation hazards for future epidemiological studies, which in turn will help refine dosimetric models. In the long term perspective, it is thought desirable to know with a good accuracy the risk factor for exposure to long-lived dust in mines and mills, it is necessary to collect accurate and reliable information on individual exposures to this particular radiation hazard now.

D. REFERENCES

1. International Commission on Radiological Protection (ICRP) Publication 30, "Limits for Intake of Radionuclides by Workers". Oxford, Pergamon Press (1978).
2. International Commission on Radiological Protection (ICRP) Publication 23, "Report of the Task Group on Reference Man". Oxford, Pergamon Press (1975).
3. Adams N., Hunt B.W. and Reissland J.A., "Annual Limits of Intake of Radionuclides for Workers", National Radiological Protection Board, NRPB-R82, Harwell-Didcot, U.K., (1978).
4. Hannibal L., "On the radiological Significance of Inhaled Uranium and Thorium Ore Dust", Health Physics, Vol. 42, 367-371 (1982).
5. Johnson J.R., "A Review of the Dosimetry from Inhalation of Long-Lived Alpha Activity in Ore Dust", Proceedings of the International Conference on Occupational Radiation Safety in Mining, Toronto (1984).
6. Jammet, H., "Les Recommendations de la Commission Internationale de Protection contre les Radiations dans les mines et usines d'uranium, Vassivieres (France) 1980.